The following full text is a preprint version which may differ from the publisher's version.

For additional information about this publication click this link.
http://hdl.handle.net/2066/94074

Please be advised that this information was generated on 2019-12-27 and may be subject to change.
Search for New Physics in the Dijet Mass Distribution using 1 fb⁻¹ of pp Collision Data at √s = 7 TeV collected by the ATLAS Detector

ATLAS Collaboration

Invariant mass distributions of jet pairs (dijets) produced in LHC proton-proton collisions at a centre-of-mass energy √s = 7 TeV have been studied using a data set corresponding to an integrated luminosity of 1.0 fb⁻¹ recorded in 2011 by ATLAS. Dijet masses up to ∼ 4 TeV are observed in the data, and no evidence of resonance production over background is found. Limits are set at 95% CL for several new physics hypotheses: excited quarks are excluded for masses below 2.99 TeV, axigluons are excluded for masses below 3.32 TeV, and colour octet scalar resonances are excluded for masses below 1.92 TeV.

I. Introduction

The Standard Model (SM) description of high energy proton-proton (pp) collisions is based on the framework of quantum chromodynamics (QCD) in the perturbative regime, where the most energetic collisions result from the 2 → 2 scattering of a pair of partons (quarks or gluons). Partons emerging from the collision shower and hadronise, in the simplest case producing two jets of particles, a “dijet”, that may be reconstructed to determine the dijet invariant mass, mjj, the mass of the two-parton system.

Previous studies of dijet mass distributions [1–6] have shown that these analyses are sensitive to the highest mass scales accessible with hadronic final states. In the present study, the dijet mass distribution is examined in a search for resonances due to new phenomena localised near a given mass, employing a data-driven background estimate that does not rely on detailed QCD calculations.

In addition to new physics benchmarks used in previous ATLAS dijet analyses, namely excited quarks (q*) [7, 8], and axigluons [9, 10], the present study includes a third hypothetical object: the colour octet scalar (s8), one of many possible exotic colour resonances [11]. Any of these objects could produce a peak in the dijet spectrum in the vicinity of their mass.

The present study is based on pp collisions at a centre-of-mass (CM) energy of 7 TeV produced at the CERN Large Hadron Collider (LHC), measured by the ATLAS detector. This data set corresponds to an integrated luminosity of 36 pb⁻¹ [6]. Excited quarks were excluded below 2.15 TeV, and axigluons below 2.10 TeV. The CMS Collaboration has recently completed a dijet resonances analysis in 1.0 fb⁻¹ of 2011 data, excluding excited quarks below 2.49 TeV and axigluons below 2.47 TeV, along with other limits [13].

A detailed description of the ATLAS detector is available in [14]. The detector is instrumented over almost the entire solid angle around the pp collision point with layers of tracking detectors, calorimeters, and muon chambers. Jet measurements are made using a finely segmented calorimeter system designed to detect the high energy jets that are the focus of this study with high efficiency and excellent energy resolution. ATLAS has a three-level trigger system, with the first level trigger (L1) being based on custom-built hardware and the two higher level triggers (HLT) being realised in software.

ATLAS uses a right-handed coordinate system with the z-axis along the beam pipe. The x-axis points to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r, φ) are used in the transverse plane, φ being the azimuthal angle. The pseudorapidity is defined in terms of the polar angle θ as η = −ln tan(θ/2). Transverse momentum and energy are defined as p_T = p sin θ and E_T = E sin θ, respectively.

The dijet mass, mjj, is derived from the vectorial sum of the four-momenta of the two highest p_T jets in the event. Kinematic criteria based on momentum and angular variables are applied to increase the sensitivity to centrally produced high mass resonances.

The angular distribution for 2 → 2 parton scattering is predicted by QCD in the CM frame of the colliding partons, which moves along the beamline due to the differing momentum fractions (Bjorken x) of the colliding partons. If E is the jet energy and p_T is the z-component of the jet’s momentum, the rapidity of the jet is given by y = 1/2 ln(E + p_T/E − p_T). The rapidities of the two highest p_T jets are denoted by y1 and y2, and the corresponding rapidity of these partons in their mutual CM frame is y* = 1/2(y1 − y2).

II. Jet reconstruction and event selection

Individual jets are reconstructed using the anti-k_t jet clustering algorithm [13, 16] with the distance parameter R = 0.6. The inputs to this algorithm are clusters [17] of calorimeter cells with energy depositions significantly above the measured noise. Jet four-momenta are constructed as the vectorial sum of clusters of cells, treating each cluster as an (E, p_T) four-vector with zero mass, assuming that the corresponding particle stems from the primary vertex.

The jet four-momenta are then corrected [18] as a function of η and p_T for various effects, the largest of which are the hadronic shower response and detector material distribution. This is done using a calibration
scheme based on Monte Carlo (MC) studies including full detector simulation, and validated with extensive testbeam \cite{10} and collision data \cite{20,22} studies. Measured dijet mass distributions are not corrected for detector resolution, which, in terms of mass smearing, is \( \sigma_{m_{jj}} \approx 5\% \) at \( m_{jj} \approx 1\) TeV, drops to 4.5\% at 2 TeV, and asymptotically approaches 4\% at \( m_{jj} \) of 5 TeV and above.

The event selection starts with the first-level trigger, which selects events that have at least one large transverse energy deposition in the calorimeters, with the transverse energy threshold increasing over the period of the data-taking as the instantaneous luminosity of the LHC \( pp \) collisions increased.

To achieve the highest possible effective integrated luminosity, the current data set has been recorded using a jet trigger that was usually not prescaled. The chosen trigger has a nominal jet \( p_T \) threshold of 180 GeV. After applying all other analysis cuts, \( m_{jj} \) is required to be greater than 717 GeV in order to attain a trigger efficiency of at least 99\% over the full range of the dijet mass distribution.

Events are required to have a primary collision vertex defined by at least five charged-particle tracks. Events with a poorly measured jet \( p_T \) greater than 30\% of the \( p_T \) of the next-to-leading jet are vetoed, to avoid cases where such a jet would cause incorrect identification of the two leading jets. This rejects less than 0.002\% of the events.

Additional kinematic criteria are applied, requiring that the two leading jets each satisfy \( |y_j| < 2.8 \) and that the rapidity in the parton CM frame satisfies \( |y^*| < 0.6 \). These criteria favour central collisions and have been shown, based on studies of expected signals and QCD background, to optimise the analysis sensitivity.

A final selection is made to avoid the calorimeter region from -0.1 to 1.5 in \( \eta \) and from -0.9 to -0.5 in \( \phi \), which was in large part affected by readout problems for most of the data used in these studies. Events with jets in this region are discarded. This requirement reduces the data set by 3.7\%.

III. Comparing data to a smooth background

The observed dijet mass distribution after all selection cuts is shown in Fig. 1. As in the previous ATLAS studies, the \( m_{jj} \) spectrum is fit to the smooth functional form

\[
f(x) = p_1 (1 - x)^{p_2} x^{p_3 + p_4 \ln x},
\]

where \( x \equiv m_{jj}/\sqrt{s} \) and the \( p_i \) are fit parameters. This ansatz has been shown empirically to accurately model the steeply falling QCD dijet mass spectrum \cite{3,6}. The \( m_{jj} \) bins are of variable width, increasing from \( \sim 50 \) to \( \sim 200 \) GeV for dijet masses from 0.85 to 4.5 TeV, respectively, to optimise the performance of the resonance search algorithm discussed in the next section.

The bottom plot of Fig.1 shows the significance, in standard deviations, of the difference between the data and the prediction in each bin. These are purely statistical, and based on Poisson distributions. The contents of a given bin are used to determine the \( p \)-value - the probability of the background fluctuating higher than the observed excess, or lower than the observed deficit. The \( p \)-value is transformed to a significance, in terms of an equivalent number of standard deviations (the \( z \)-value).

Where there is an excess (deficit) in data in a given bin, the significance is plotted as positive (negative). In mass bins with small expected number of events, where the observed number of events is similar to the expectation, the Poisson probability of a fluctuation at least as high (low) as the observed excess (deficit) can be greater than 50\%, as a result of the asymmetry of the Poisson distribution. Such bins present no statistical interest and, for simplicity, bars are not drawn for them.

To determine the degree of consistency between data and the fitted background, the \( p \)-value of the fit is obtained by calculating the \( \chi^2 \) from the data, and comparing this result to the \( \chi^2 \) distribution obtained from pseudoexperiments. The resulting \( p \)-value is 0.96, showing that there is good agreement between the data and the functional form.

![FIG. 1. The reconstructed dijet mass distribution (filled points) fitted with a smooth functional form describing the QCD background. The bin-by-bin significance of the data-background difference is shown in the lower panel. Vertical lines show the most significant excess found by the BUMP-HUNTER algorithm (see text).](image)

IV. Search for resonances

As a more sensitive test, the BUMP-HUNTER algorithm \cite{24,25} is used to establish the presence or absence of a resonance in the dijet mass spectrum. To optimise the sensitivity of this algorithm, the \( m_{jj} \) binning strategy is to establish a minimum width for resonances to be considered physical. To this end, the relatively narrow \( q^* m_{jj} \) template from full MC simulation \cite{20}, described below for subsequent studies, has been used to establish
the binning. If the width of the resonance is defined as 
\pm 1 \sigma, the greatest sensitivity at the minimum width is 
achieved by setting the bin width to 1 \sigma, half the reso-
nance width. The final result of this procedure is that 
the variable bin sizes are typically 6.5\% to 7.0\% of \( m_{jj} \)
in width, somewhat wider than detector resolution due
to the finite natural width of \( q^* \), which varies between
about 3\% and 3.5\% of the \( q^* \) mass.

In the current implementation, the BumpHunter algo-

rithm searches for the signal window with the most
significant excess of events above background. Starting
with a two-bin window, the algorithm increases the sig-
nal window and shifts its location until all possible bin
ranges, up to half the mass range spanned by the data,
have been tested. The most significant departure from
the smooth spectrum (“bump”) is defined by the set of
bins that have the smallest probability of arising from a
background fluctuation assuming Poisson statistics.

The BumpHunter algorithm accounts for the so-
called “look elsewhere effect” (or “trials factor ef-
cfect”) \[27\] by performing a series of pseudoexperiments
to determine the probability that random fluctuations in
the background-only hypothesis would create an excess
as significant as the one observed anywhere in the spec-
trum. Variable width binning reduces the penalty due
to this effect, while retaining sensitivity.

To prevent any new physics signal from biasing the
background estimate, if the biggest local excess from the
background fit has a p-value smaller than 0.01, this region
is excluded and a new background fit is performed. No
such exclusion is needed for this data set.

The most significant discrepancy identified by the
BumpHunter algorithm in the observed dijet mass dis-
tribution reported in Fig. 1 is a 2-bin excess in the inter-
val 1.16 to 1.35 TeV. The probability of observing such
an excess or larger somewhere in the mass spectrum for
a background only hypothesis is 0.82. This test shows
that there is no evidence for a resonance signal in the
\( m_{jj} \) spectrum.

V. New physics models

Exclusion limits are set on three new physics scenarios
expected to give rise to resonant dijet production.

For the first of these, excited quarks, \( q^* \), a \( qg \to q^* \)
production model \[25, 27\] is used, with the assumption of
spin 1/2 and quark-like SM coupling constants. The
compositeness scale (A) is set to the \( q^* \) mass. Signal
events are produced using the Pythia event generator
\[28\], a leading-order parton-shower MC generator,
with the MRST2007LO* \[29\] parton distribution func-
tions (PDF’s), with settings established by the ATLAS
default MC10 \[30\] Monte Carlo tune. The renormaliza-
tion and factorization scales are set to the mean \( p_T \)
of the two leading partons for each event. Pythia is also
used to decay the excited quarks to all possible SM final
states, which are predominantly qg, but also qq, \( qW, qZ, \) and \( q\gamma \). The generated events are passed through
the detailed simulation of the ATLAS detector \[20\], which
uses the GEANT4 package \[31\] for simulation of particle
transport, interactions, and decays. The simulated
events are then reconstructed in the same way as the
data to produce predicted dijet mass distributions that
can be compared with the observed distributions.

The second model is axigluon production \[9, 10\] via an
interaction given by the Lagrangian

\[
\mathcal{L}_{Aqg} = g_{QCD} A_{\mu}^{A} A_{\nu}^{\mu} \gamma_5 q_1, \tag{2}
\]

where \( g_{QCD}^2 = 4\pi \alpha_s \) is the QCD coupling constant and \( A_{\mu}^{A} \) is the axigluon field representing a massive state with
axial coupling to quarks. Parity conservation prevents
the axigluon from coupling to two gluons. Parton-level
events are generated, at leading-order approximation, us-
ing the CalcHEP Monte Carlo package \[32\], for chosen
masses, \( m \), of the axigluon. The MRST2007LO* PDF
set was used. The axigluon dijet mass has longer tails at
high and low masses than the \( q^* \) distribution, but these
two shapes are interchangeable within the range 0.7m to
1.3m for all masses of interest. Since the axigluon tails
outside this range are well below the SM background,
the predicted signal may be analyzed by cutting events
beyond this range and accounting for the reduced ac-
ceptance. The axigluon MC prediction for \( \sigma \times A \), the pro-
duction cross section within the acceptance, is defined
to include these cuts by applying them at the level of
CalcHEP generation, along with the kinematic cuts in
\( p_T \) and rapidity. In the limit setting analysis, these
axigluon results are compared to the observed \( \sigma \times A \) limits
from the \( q^* \) analysis. This method is discussed in more
detail in Section VI.

The third resonant hypothesis, the colour octet scalar
(s8) model, is a prototype for many possible exotic
coloured resonances \[12\]. Colour octet resonances can
couple to gluons, which have large parton luminosity at
the LHC. One possible interaction is

\[
\mathcal{L}_{gg8} = g_{QCD}^4 d^{ABC} A_{8}^{\alpha} A_{8}^{\alpha} S_{8}^{A} F_{\mu\nu}^{\alpha} F_{C,\mu\nu}, \tag{3}
\]

where \( S_{8}^{A} \) is the colour octet scalar field, \( \kappa_8 \) is the scalar
coupling (assumed to be unity), and \( d^{ABC} \) is the SU(3)
isoscalar factor; \( A_8 \) is the new physics scale which is set
to the resonance mass, \( M_{s8} \). This model leads to a very
simple event topology, with two gluons in the initial and
final states, yielding high \( p_T \) dijets. MadGraph 5 \[33\]
is used to generate parton level events at leading-order ap-
proximation. Pythia with CTEQ6L1 PDF’s is used in this
generation, with the ATLAS MC09’ tune \[34\]. These
samples are processed through the full ATLAS detector
simulation.

The observed limits on s8 are less strict than the corre-
sponding \( q^* \) limits, in part because the s8 signal is much
wider than \( q^* \). Much of this width increase is due to fi-
dal state radiation, which is larger for gluon-jets than for
quark-jets. In addition, the initial state for s8 production
contains gluons, which have small parton density at high
mass. Thus, s8 are much more likely to be off-mass-shell
than \( q^* \).
VI. Model dependent limit setting

In the absence of any observed significant discrepancy from the zero-signal hypothesis, the Bayesian method documented in [6] is used to set 95% credibility-level (CL) upper limits.

Bayesian credibility intervals are set by defining a posterior probability density from the Poisson likelihood function for the observed mass spectrum, obtained by a fit to the background functional form and a signal shape derived from MC simulations. A prior probability density constant in all positive values of signal cross section, and zero at negative values, is used. The posterior probability is then integrated to determine the 95% CL for a given range of models, usually parameterised by the mass of the resonance.

Limits are determined on $\sigma \times A$ for a hypothetical new particle decaying into dijets. The acceptance includes all reconstruction steps and analysis cuts described above, and assumes that the trigger is fully efficient. (The efficiency is greater than 99% for all analyses.)

The effects of systematic uncertainties due to the knowledge of the luminosity and of the jet energy scale (JES) are included. The luminosity uncertainty for the 2011 data is 3.7% [33]. The systematic uncertainty on the JES is taken from the 2010 data [18] analysis, and is adapted to the 2011 analysis taking into account in particular the new event pileup conditions (described below). The JES uncertainty shifts resonance peaks by less than 4%. The background parameterization uncertainty is taken from the fit results, as described in [6]. The effect of the jet energy resolution (JER) uncertainty is found to be negligible. All of these uncertainties are incorporated into the fit by varying all sources according to Gaussian probability distributions and convolving them with the Bayesian posterior probability distribution. Credibility intervals are then calculated numerically from the resulting convolutions. No uncertainties are associated with the theoretical model of new physics, as in each case the model is a benchmark that incorporates a specific choice of model parameters, of PDF set, and of MC tune. Previous ATLAS studies have already explored the impact of different MC tunes and PDF sets on the $q^*$ theoretical prediction [4].

In 2011, the instantaneous luminosity has risen to a level where corrections must be made for multiple $pp$ collisions occurring in the same bunch crossing ("pileup"), whose presence affects the measurement of calorimeter energy depositions associated with the hard-scattering event under study. All simulated samples used in this analysis include a Poisson distributed number of MC minimum bias events added to the hard interaction to account for "in-time" pileup caused by additional collisions in the same bunch crossing. Further account must be taken of "out-of-time" pileup originating from collisions in bunches preceding or following the one of interest, due to the long response time of the liquid argon calorimeters. With the 50 ns bunch spacing in the LHC for these data, up to 12 preceding bunches and 1-2 follow-
FIG. 2. The 95% CL upper limits on $\sigma \times A$ as a function of particle mass (black filled circles). The black dotted curve shows the 95% CL upper limit expected from Monte Carlo and the light and dark yellow shaded bands represent the 68% and 95% contours of the expected limit, respectively. Theoretical predictions for $\sigma \times A$ are shown in (a) for excited quarks (blue dashed) and axigluons (green dot-dashed), and in (b) for colour octet scalar resonances (blue dashed). For a given new physics model, the observed (expected) limit occurs at the crossing of its $\sigma \times A$ curve with the observed (expected) 95% CL upper limit curve.

FIG. 3. The 95% CL upper limits on $\sigma \times A$ for a simple Gaussian resonance decaying to dijets as a function of the mean mass, $m_\sigma$, for four values of $\sigma_\sigma/m_\sigma$, taking into account both statistical and systematic uncertainties.

VIII. Conclusion

The dijet mass spectrum measured by the ATLAS experiment has been examined in a search for resonances from new phenomena, using 1.0 fb$^{-1}$ of 7 TeV $pp$ collision data taken in 2011. The observed distribution, which extends up to masses of $\approx 4$ TeV, is in good agreement with a smooth function representing the SM expectation. No evidence for the production of new resonances is found. 95% CL mass limits using Bayesian methodology have been set in the context of several models of new physics, as summarized in Table I. For excited quarks and axigluons, the current results exceed the limits obtained by ATLAS with the 2010 data by approximately one TeV. Exclusion limits on colour octet scalar resonances have been established for the first time in ATLAS. The limits reported in this paper are the most stringent to date.

<table>
<thead>
<tr>
<th>Model</th>
<th>95% CL Limits (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Expected</td>
</tr>
<tr>
<td>Excited Quark $q^*$</td>
<td>2.81</td>
</tr>
<tr>
<td>Axigluon</td>
<td>3.07</td>
</tr>
<tr>
<td>Colour Octet Scalar</td>
<td>1.77</td>
</tr>
</tbody>
</table>

Table I. The 95% CL mass lower limits for the models of new physics examined in this study. They have been obtained with Bayesian analyses and include systematic uncertainties.
Appendix: Setting limits on new models

The following procedure is appropriate for resonances that are approximately Gaussian near the core, and with tails that are well below the background. For convenience, the results of Fig. 5 are provided in Table II.

(1) For a MC sample generated with the mass of the hypothetical new particle set to \( M \), compute an initial acceptance including the branching ratio into dijets. Then apply the kinematic cuts on the parton \( \eta, p_T \), and \( |y^*| \) used in this analysis. (2) Approximate the reduction of acceptance due to the calorimeter (temporary) readout problem by eliminating events where a parton enters the region \(-0.1 \text{ to } 1.5 \) in \( \eta \), and \(-0.9 \text{ to } -0.5 \) in \( \phi \). (Indicatively, the acceptance of \( q^* \) is reduced by a factor 0.92.) (3) Smear the signal mass distribution to reflect the detector resolution. In the absence of a better detector simulation tool, use the mass resolution given in Section II, which is derived from full ATLAS simulation. (4) Since a Gaussian signal shape has been assumed in determining the limits, any long tails in the reconstructed \( m_{jj} \) should be removed in the sample under study. The recommendation (based on optimization using \( q^* \) templates) is to retain events with \( m_{jj} \) between 0.8\( m \) and 1.2\( m \). The mean mass, \( m \), of this truncated signal should be calculated. (5) The fraction of MC events surviving the first four steps determines the modified acceptance, \( \mathcal{A} \). (6) From Table II select \( m_G \) so that \( m_G = m \). If the exact value of \( m \) is not among the listed values of \( m_G \), check the limit for the two values of \( m_G \) that are directly above and below \( m \), and use the larger of the two limits to be conservative. (7) To retain enough of the information in the full signal template, and at the same time reject tails that would invalidate the Gaussian approximation, the following truncation procedure is recommended. For this mass point, choose a value of \( \sigma_G/m_G \) such that the width \( 2\sigma_G \) is well contained in the (truncated) mass range. For \( q^* \) a good choice is empirically found to be \( \sigma_G = (1.2M - 0.8M)/5 \). This \( \sigma_G \) corresponds to a Gaussian distribution contained within the truncation interval of \([0.8M, 1.2M]\), since the interval \([0.8M, 1.2M]\) corresponds to \([m_G - 2.5\sigma_G, m_G + 2.5\sigma_G]\). For the \( q^* \) case a good choice is \( \sigma_G = (1.2M - 0.8M)/5 \) so that 95\% of the Gaussian spans \( 4 \times (0.4/5)M \). Use this value to pick the closest \( \sigma_G/m_G \) value, rounded up to be conservative. (8) Compare the tabulated 95\% CL upper limit corresponding to the chosen \( m_G \) and \( \sigma_G/m_G \) values to the \( \sigma \times \mathcal{A} \) obtained from the theoretical cross section of the model multiplied by the acceptance defined in step (5) above.

Acknowledgements

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DNSRC and Lundbeck Foundation, Denmark; ARTEMIS, European Union; INFN, IN2P3-CNRS, CEA-DSM/IRFU, France; GNAS, Geor-
gia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT, Greece; ISF, MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNiSW, Poland; GRICES and FCT, Portugal; MERSYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MVZT, Slovenia; DST/NRF, South Africa; MEXT, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Canton of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

31 (a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
32 (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Modern Physics, University of Science and Technology of China, Anhui; (c) Department of Physics, Nanjing University, Jiangsu; (d) High Energy Physics Group, Shandong University, Shandong, China
33 Laboratoire de Physique Corpusculaire, Clermont Université et Université Blaise Pascal and CNRS/IN2P3, Aubière Cedex, France
34 Nevis Laboratory, Columbia University, Irvington NY, United States of America
35 Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
36 (a) INFN Gruppo Collegato di Cosenza; (b) Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy
37 Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology, Krakow, Poland
38 The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
39 Physics Department, Southern Methodist University, Dallas TX, United States of America
40 Physics Department, University of Texas at Dallas, Richardson TX, United States of America
41 DESY, Hamburg and Zeuthen, Germany
42 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
43 Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany
44 Department of Physics, Duke University, Durham NC, United States of America
45 SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
46 Fachhochschule Wiener Neustadt, Johannes Gutenbergstrasse 3, 2700 Wiener Neustadt, Austria
47 INFN Laboratori Nazionali di Frascati, Frascati, Italy
48 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg i.Br., Germany
49 Section de Physique, Université de Genève, Geneva, Switzerland
50 (a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy
51 Institute of Physics and HEP Institute, Georgian Academy of Sciences and Tbilisi State University, Tbilisi, Georgia
52 II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
53 SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
54 II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
55 Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
56 Department of Physics, Hampton University, Hampton VA, United States of America
57 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
58 (a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (c) ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
59 Faculty of Science, Hiroshima University, Hiroshima, Japan
60 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
61 Department of Physics, Indiana University, Bloomington IN, United States of America
62 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
63 University of Iowa, Iowa City IA, United States of America
64 Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
65 Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
66 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
67 Graduate School of Science, Kobe University, Kobe, Japan
68 Faculty of Science, Kyoto University, Kyoto, Japan
69 Kyoto University of Education, Kyoto, Japan
70 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
71 Physics Department, Lancaster University, Lancaster, United Kingdom
72 (a) INFN Sezione di Lecce; (b) Dipartimento di Fisica, Università del Salento, Lecce, Italy
73 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
74 Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
75 Department of Physics, Queen Mary University of London, London, United Kingdom
76 Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
77 Department of Physics and Astronomy, University College London, London, United Kingdom
78 Laboratoire de Physique Nucléaire et de Hautes Énergies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
79 Fysiska institutionen, Lunds universitet, Lund, Sweden
80 Departamento de Física Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
81 Institut für Physik, Universität Mainz, Mainz, Germany
l'Energie des Sciences Techniques Nucleaires, Rabat; (c) Université Cadi Ayyad, Faculté des sciences Semlalia Département de Physique, B.P. 2390 Marrakech 40000; (d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; (e) Faculté des Sciences, Université Mohammed V, Rabat, Morocco
136 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l'Energie Atomique), Gif-sur-Yvette, France
137 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
138 Department of Physics, University of Washington, Seattle WA, United States of America
139 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
140 Department of Physics, Shinshu University, Nagano, Japan
141 Fachbereich Physik, Universität Siegen, Siegen, Germany
142 Department of Physics, Simon Fraser University, Burnaby BC, Canada
143 SLAC National Accelerator Laboratory, Stanford CA, United States of America
144 (a) Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
145 (a) Department of Physics, University of Johannesburg, Johannesburg; (b) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
146 (a) Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden
147 Physics Department, Royal Institute of Technology, Stockholm, Sweden
148 Department of Physics and Astronomy, Stony Brook University, Stony Brook NY, United States of America
149 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
150 School of Physics, University of Sydney, Sydney, Australia
151 Institute of Physics, Academia Sinica, Taipei, Taiwan
152 Department of Physics, Technion: Israel Inst. of Technology, Haifa, Israel
153 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
154 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
155 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
156 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
157 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
158 Department of Physics, University of Toronto, Toronto ON, Canada
159 (a) TRIUMF, Vancouver BC; (b) Department of Physics and Astronomy, York University, Toronto ON, Canada
160 Institute of Pure and Applied Sciences, University of Tsukuba, Ibaraki, Japan
161 Science and Technology Center, Tufts University, Medford MA, United States of America
162 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
163 Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
164 (a) INFN Gruppo Collegato di Udine; (b) ICTP, Trieste; (c) Dipartimento di Fisica, Università di Udine, Udine, Italy
165 Department of Physics, University of Illinois, Urbana IL, United States of America
166 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
167 Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelecronicà de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
168 Department of Physics, University of British Columbia, Vancouver BC, Canada
169 Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
170 Waseda University, Tokyo, Japan
171 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
172 Department of Physics, University of Wisconsin, Madison WI, United States of America
173 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
174 Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
175 Department of Physics, Yale University, New Haven CT, United States of America
176 Yerevan Physics Institute, Yerevan, Armenia
177 Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France
a Also at Laboratorio de Instrumentacão e Física Experimental de Partículas - LIP, Lisboa, Portugal
b Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal
c Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
d Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
e Also at TRIUMF, Vancouver BC, Canada
f Also at Department of Physics, California State University, Fresno CA, United States of America
g Also at Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology, Krakow, Poland
Also at Fermilab, Batavia IL, United States of America

Also at Department of Physics, University of Coimbra, Coimbra, Portugal

Also at Università di Napoli Parthenope, Napoli, Italy

Also at Institute of Particle Physics (IPP), Canada

Also at Department of Physics, Middle East Technical University, Ankara, Turkey

Also at Louisiana Tech University, Ruston LA, United States of America

Also at Group of Particle Physics, University of Montreal, Montreal QC, Canada

Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany

Also at Manhattan College, New York NY, United States of America

Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China

Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipeí, Taiwan

Also at High Energy Physics Group, Shandong University, Shandong, China

Also at Section de Physique, Université de Genève, Geneva, Switzerland

Also at Departamento de Física, Universidade de Minho, Braga, Portugal

Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America

Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary

Also at California Institute of Technology, Pasadena CA, United States of America

Also at Institute of Physics, Jagiellonian University, Krakow, Poland

Also at Department of Physics, Oxford University, Oxford, United Kingdom

Also at Institute of Physics, Academia Sinica, Taipei, Taiwan

Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America

Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat a l’Energie Atomique), Gif-sur-Yvette, France

Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France

Also at Department of Physics, Nanjing University, Jiangsu, China

Deceased